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Control Issues for Microelectromechanical Systems

ABSTRACT

MEMS is a disruptive technology that requires unparalleled synergy between previously unrelated fields such as biology and microelectronics. With successful integration of electrical, mechanical, material, computer science, control, and bioengineering, new MEMS applications are emerging. Progress is facilitated by the fact that silicon, which is among the world's best-characterized materials [2], surpasses stainless steel in yield strength and aluminum in strengthto-weight ratio. Despite their small size on the order of that of a human hair, however, MEMS devices are no less mechanical or complex than bridges and skyscrapers.

The first closed-loop controlled MEMS devices were sensors that included on-chip actuators to enhance the accuracy of the measurement process, either by force/position amplification or by better presenting the measured quantity to the sensor. Below, we highlight some MEMS control issues. An overview of MEMS control is given in [1].

Control Issues for Microelectromechanical Systems

B. BOROVIC, F.L. LEWIS, W. McCULLEY, AI QUN LIU, E.S. KOLESAR, and D.O. POPA

Most MEMS technologists do not have a background in control technology. Without the help of control systems engineers, development cycles will be stretched.
—Janusz Bryzek, Keynote Talk, CDC 2003, Maui, Hawaii

Unlike semiconductor integrated circuits (ICs), micro-electromechanical systems (MEMS) combine sensors, actuators, mechanical structures, electronics, and optics on a single substrate. MEMS are the next step in the silicon revolution that began 40 years ago. Currently, MEMS are in an exponential growth stage such as that enjoyed by the semiconductor industry.

The first MEMS devices were discrete open-loop pressure sensors developed in the 1960s [1]. The successful integration of MEMS and integrated circuits began in the 1980s, resulting in accelerometers, inkjet print heads, and gyro sensors as well as devices for HDTV displays and drug delivery systems. The availability of tabletop analytical instruments for high-performance gas and liquid chromatography (HPGC and HPLC), DNA polymerase chain reaction amplification and identification, atomic force and scanning tunneling microscopes (AFM and STM), biohazard and drug-screening devices, and chemical assays are a direct result of the integration of IC electronics with MEMS and the associated miniaturization and cost reduction.

MEMS is a disruptive technology that requires unparalleled synergy between previously unrelated fields such as biology and microelectronics. With successful integration of electrical, mechanical, material, computer science, control, and bioengineering, new MEMS applications are emerging. Progress is facilitated by the fact that silicon, which is among the world's best-characterized materials [2], surpasses stainless steel in yield strength and aluminum in strength-to-weight ratio. Despite their small size on the order of that of a human hair, however, MEMS devices are no less mechanical or complex than bridges and skyscrapers.

The first closed-loop controlled MEMS devices were sensors that included on-chip actuators to enhance the accuracy of the measurement process, either by force/position amplification or by better presenting the measured quantity to the sensor. Below, we highlight some MEMS control issues. An overview of MEMS control is given in [1].

MICROFORCES AND REAL ESTATE

The forces that come into play at the micro level are different from those at the macro level. Gravity, which is often relied on in control and assembly systems for macro systems, plays only a minimal role at the micro level. Instead, the dominant forces include electrostatic, van der Waals, surface tension, and stiction. In many applications, active control is needed to offset these forces. For instance, in microrobotic grippers, grasping and release of "sticky" parts is a major issue. The use of fixtures for holding parts in microassembly takes on increased importance. In macro assembly, 30% of new product development costs are directed toward fixture design, whereas in MEMS devices both the parts and the fixtures can be fabricated during the same production run (batch processing). This ability means that fixtures can be tailored for each batch of fabricated parts, significantly improving assembly efficiency and ease. On the other hand, including fixtures on the same chip reduces the area available for fabricating the usable operational parts. This situation leads to the issue of chip real estate, that is, the chip area available for operational parts. Along the same lines, in the macro world (think of robots) the controlled device is large, while the actuators and sensors are small. However, in MEMS, the device, the actuators, sensors, and control system in IC-processing electronics are all
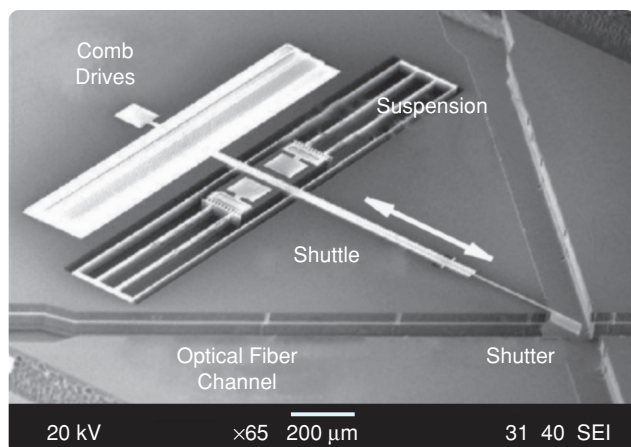
FIGURE 1 A MEMS device that can be used either as an optical switch or variable optical attenuator. Optical fiber grooves (channels) and the shutter are clearly visible. This device was fabricated at the Nanyang Technological University MEMS Optics and Bioengineering Lab.

Labels in figure: Comb Drives, Suspension, Shuttle, Optical Fiber Channel, Shutter, 20 kV, ×65, 200 μm, 31 40 SEI

of similar size. Therefore, adding sensors and actuators to MEMS devices is a complex design decision.

OPTICAL FIBER SWITCH

Although MEMS can benefit from the knowledge and experience of control practitioners, control techniques cannot be applied directly and naively. For example, a mechanical variable optical attenuator (VOA) (Figure 1) can improve the switching response of optical fiber systems. The controlled device is the shutter mounted at the tip of the shuttle arm, whose function is to modulate an optical beam in the space between optical fibers. A mirror is mounted on the shutter to allow switching among fiber-optic channels. The actuator is an electrostatic comb drive with two sets of fingers to drive the shuttle forward and backward. Note that the dimensions of the comb drive actuator are similar to those of the shuttle/shutter device. An additional suspension keeps the motion in the desired direction, performing a function similar to bearings in a robot arm. The key point is that the device, actuator, and suspension are commensurate in size, unlike the macro case where bearings and actuators are much smaller than robot arms.

## OPEN-LOOP VERSUS CLOSED-LOOP CONTROL

The VOA device, typical of MEMS systems, is a complex system having a rigid mode as well as vibrational modes in longitudinal, lateral, and out-of-plane motion. To obtain sufficient speed of response in such systems without exciting high-frequency modes, input shaping methods [3], [4] are often used to avoid exciting the vibratory modes. Based on the desired trajectory of the shutter, input signals can be produced using convolution-based preshaping methods. The advantage of such methods is that no additional electronics are needed to implement controllers. However, preshaping usually requires an accurate mathematical model of the device, which may not be available due to fabrication inconsistencies and, thus, lack of repeatability of the device parameters. In [1], a gain scheduling approach is used to compensate for device variability, while [2] discusses built-in circuitry for testing and calibrating MEMS devices along with the capability to program the calibration constants directly into an IC fabricated with the device.

To achieve increased precision and faster response, closed-loop control is required. The closed-loop controller designed in [5] and shown in Figure 2 incorporates an inner position control loop and an outer intensity control loop. To obtain the desired response,

standard control techniques are used, including compensation of nonlinearities, such as the voltage-squared nonlinearity and the position-to-light-intensity error function erf as well as a reference feedforward term to speed up the response and improve accuracy. With the feedforward term, the closed-loop controller produces a sharp initial voltage spike similar to that obtained by input preshaping. Figure 3 shows the improvement attained by this technique in rise time, settling time, and percent overshoot compared to the open-loop response.

PHYSICAL MODELING AND FINITE ELEMENT ANALYSIS

The design of MEMS controllers relies on the availability of reasonably accurate dynamical models. However, dynamical
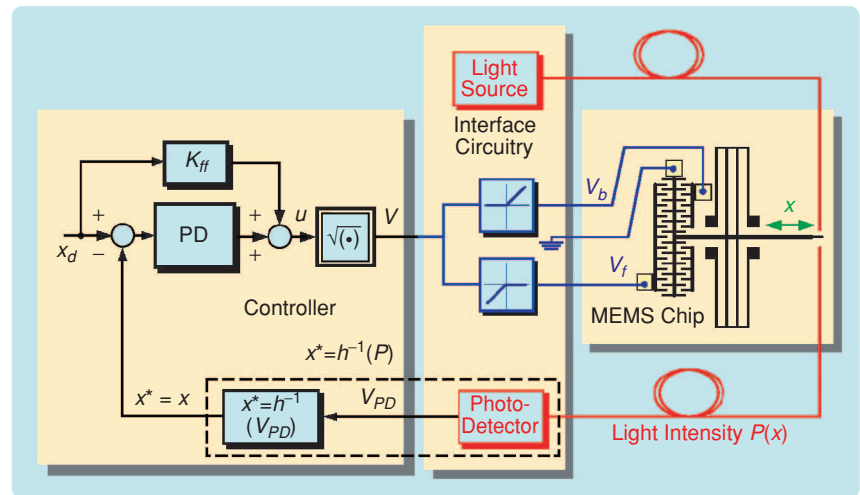

FIGURE 2 Inner position control loop of the variable optical attenuator controller. The trajectory feedforward gain K_{ff} compensates for a voltage-squared nonlinearity. An outer intensity control loop is also used [5].
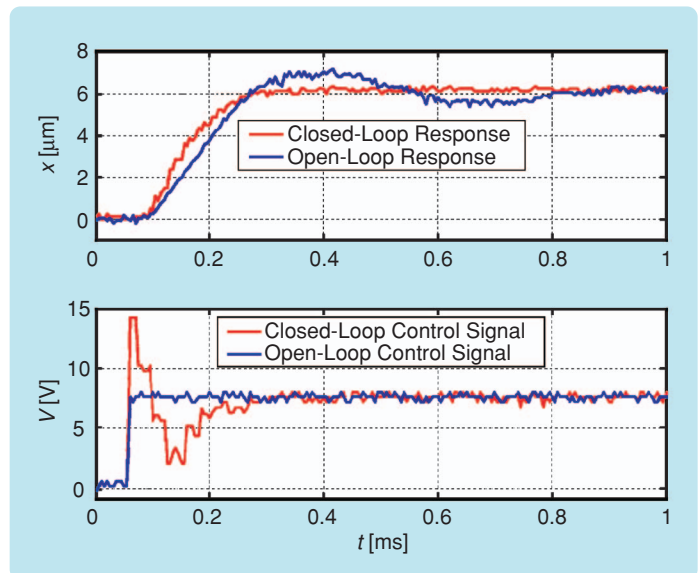
FIGURE 3 Open- and closed-loop experimental step responses of the position of the variable optical attenuator. Trajectory feedforward adds a large initial spike to the voltage, resulting in faster response [5]. A rise time of 170 μs is achieved.
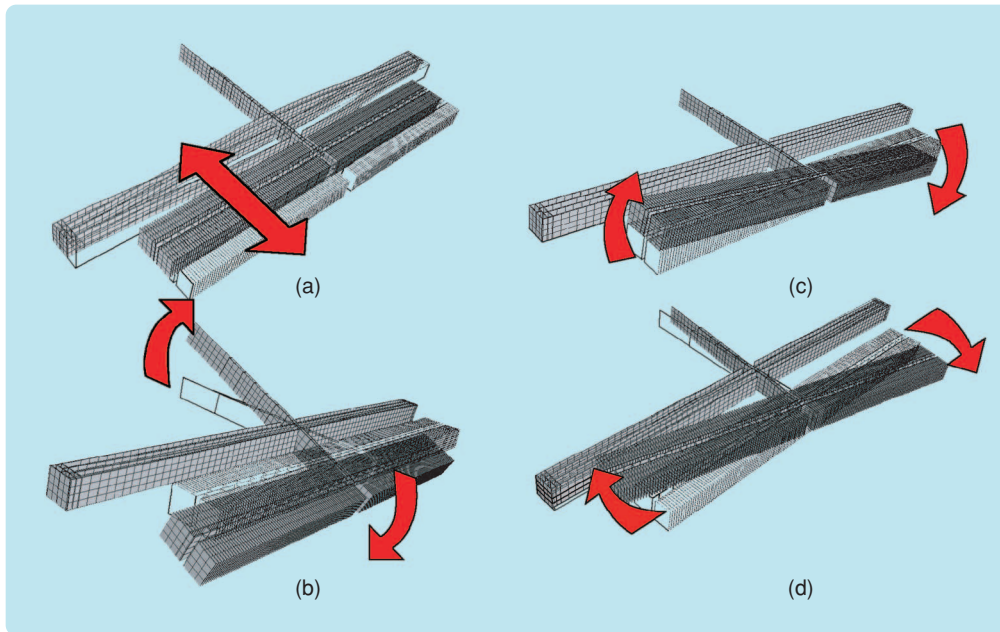
FIGURE 4 First four vibrational modes of the variable optical attenuator. In addition to the (a) main mode and (d) lateral mode, the variable optical attenuator exhibits out-of-plane motion (b) and (c). Out-of-plane motion influences both force generation and sensing.
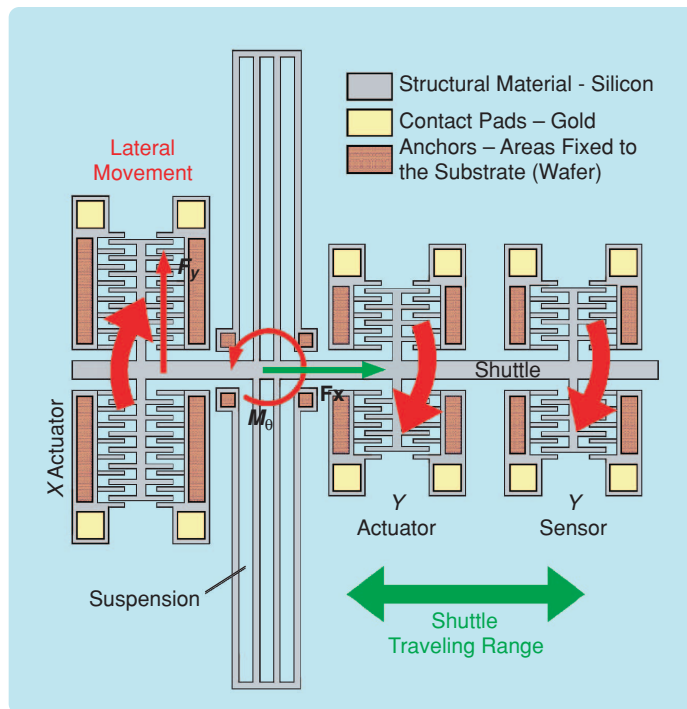
FIGURE 5 Variable optical attenuator with additional sensor and actuator functionality for lateral motion control. These additional features, along with appropriate control system design, enable a much larger shuttle stroke (patent pending).

models are not easily obtained for MEMS devices through fabrication and testing, while standard analytical modeling methods are often inadequate. Due to the silicon micromachining process and the high density of MEMS devices on a single chip, compensation and control issues must be incor-porated into the design of the device since sin-gle-pass fabrication is essential for economic viability. Therefore, all modes of functionality must be incorporated into the design phase; in the macro world, these phases might be left to testing and cali-bration [2]. Standard physical modeling prin-ciples can be used to derive distributed dynamic models for MEMS devices. Then, finite element analysis (FEA) is used to deter-mine the system para-meters, resulting in state-space models for subsequent controller design. However, FEA modeling that includes mechanical, electrical, and ther-mal effects can be time consuming. Alternatively, reduced-order FEA modeling with average tempera-ture as a state variable facilitates simulation for control design [6].

VIBRATIONAL MODES AND LATERAL INSTABILITY

MEMS devices usually have vibrational modes. In par-ticular, electrostatic drives suffer from electromechani-cal instabilities such as lateral pull-in, side pull-in, and lateral instability. Although fabricated to be symmet-ric, the actuator's comb structure is always unbal-anced, causing adjacent comb-finger electrodes to contact each other when high voltages are applied. Lateral instability decreases the stroke of the actuator due to the mechanical design of the suspension. FEA and reduced-order modeling provide the first four vibration modes of the VOA shown in Figure 4. The fourth mode involves lateral motion. Although the performance of the VOA can be improved by control-ling the lateral modes, lateral control requires addi-tional sensors and actuators. Figure 5 shows a modified design that incorporates lateral motion sen-sors and actuators to counteract lateral instability. The y-actuators consist of top and bottom comb drives. This structure also suppresses out-of-plane motion. Capaci-tive sensing is used for the y-displacement, and a bridge sensor arrangement is used to compensate stray capaci-tances and residual out-of-plane-motion effects (modes (b) and (c) in Figure 4).
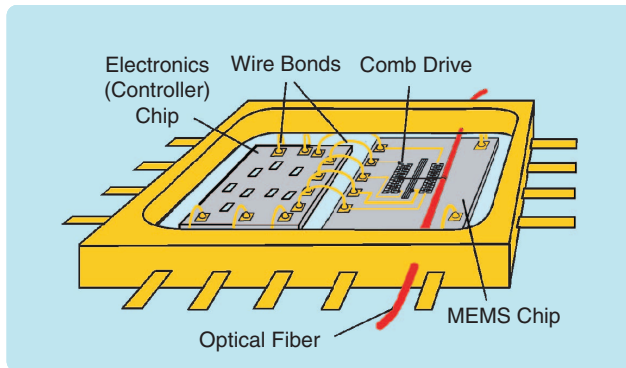
FIGURE 6 Multichip package containing MEMS device, control electronics, and optical fibers. MEMS controllers are ideally implemented in the same package or even on the same chip, and thus must have low complexity. To save space, controllers are typically implemented with operational amplifiers.

Since the added sensors and actuators significantly change the device dynamics, additional modeling based on physical principles and FEA is needed to determine the modified dynamics. Finally, on-chip signal conditioning is needed to detect capacitance changes, which are on the order of stray or parasitic capacitances. The signal conditioning now occupies significant real estate, resulting in reduced device yield per chip. A control system designed using standard robust feedback methods can compensate for lateral pull-in and significantly extend the range of travel of the mechanical shuttle.

MEMS CONTROLLER IMPLEMENTATION AND PACKAGING

The VOA controller is implemented using a dSPACE controller board with a sampling time of 12 μs, the minimum sampling time possible with this device. In practice, MEMS controllers must be integrated using fast analog VLSI devices. Consequently, the controllers must be simple.

Integration of MEMS relies on simultaneous fabrication of the device, actuators, sensors, signal conditioning, and control circuitry [7]. Figure 6 shows a multichip system design for the VOA, which includes the device, actuators, lateral sensors, controller IC chip, and optical fiber interconnect.

An additional issue for control design is that the package can change the dynamical model of the device. For instance, damping, which is difficult to model using finite element techniques, depends on the degree of vacuum and, hence, on the packaging. Control systems must be designed to be robust against variable damping coefficients in the system and other packaging effects.

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Optical Image Stabilization for Digital Cameras

BRENT CARDANI

Capturing clear, crisp pictures can be a challenge, even for professional photographers. Motion, light levels, or the use of a telephoto lens can compromise clarity. In particular, whenever a tripod is not used, snapshots may blur due to jitter. When the photographer's hands are not steady, the camera lens rotates with the camera body, and the resulting lens movement causes the focal image to blur. These problems are exacerbated when slow shutter speeds are used.

To address these problems, global electronics manufacturer Panasonic has formed a collaborative partnership with lens maker Leica. Together they have introduced an image stabilization system in the Lumix line of digital cameras. Dubbed MEGA Optical Image Stabilization (MEGA OIS), the system

detects movement of the camera before a picture is snapped.

When the photographer lines up a shot, two angular rate sensors within the Lumix camera detect pitch and yaw motion of the camera body. Shigeo Sakaue, manager of the DSC Business and Development Center in the Network Business Group, explains: "The image is stabilized by using angular rate sensors, called gyrosensors, to detect how quickly the camera is moving in both vertical and horizontal directions. Then, a corrective lens is moved in the direction opposite to that of the detected data" to counteract jitter.

A filter/amplifier circuit distinguishes between intentional panning and jitter. Information for jitter is extracted and sent to Panasonic's processor Venus Engine II. The processor calculates